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## High $K_{\alpha}$ X-ray conversion efficiency from extended source gas jet targets irradiated by ultra short laser pulses

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## Abstract

The absolute laser conversion efficiency to  $K_{\alpha}$ -like inner shell x-rays (integrated from  $K_{\alpha}$  to  $K_{\beta}$ ) is observed to be an order of magnitude higher in argon gas jets than in solid targets due to enhanced emission from higher ionization stages following ultra short pulse laser irradiation. Excluding the higher ionization stages, the conversion efficiency to near-cold  $K_{\alpha}$  is the same in gas jets as in solid targets. These results demonstrate that gas jet targets are bright, high conversion efficiency, high repetition rate, debris-free multi-keV x-ray sources for spectrally resolved scattering and backlighting of rapidly evolving dense matter.

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X-ray diagnosis of dense matter utilizes two principal types of sources. Narrow bandwidth sources, such as  $\text{He}_{\alpha}$  and  $\text{K}_{\alpha}$  emitters, are important for spectrally resolved scattering to probe high energy density states of matter, such as those found in inertial confinement fusion experiments [1, 2].  $\text{K}_{\alpha}$ -based diagnostics allow for Compton and plasmon measurements of the physical properties of dense matter [2–4]. Both narrow band and broad bandwidth (such as closely spaced lines from L and M shell emitters) sources are applied to backlight and radiograph dense plasmas [5].

Extended sources are volumetric emitters that achieve better conversion efficiency (defined as the ratio of emitted x-ray energy over incident laser energy) than is achieved by point x-ray sources such as laser irradiated foils. Novel extended sources, including doped aerogels and rare gases in Be enclosures, have achieved high conversion efficiency in the < 10 keV range (i.e. L, M, and thermal K-shell emission) when irradiated by long-pulse lasers [6, 7]. However, extremely dense states of matter, like those produced on the National Ignition Facility, require x-ray probe energies of 20-100 keV. These energies are obtainable as K-shell emission from  $Z \ge 45$  elements, with conversion efficiency that is nearly independent of Z [8].

Using specifically  $K_{\alpha}$ -like inner-shell x-ray emission also enables time-resolved plasma diagnostics, as the emission of these x-rays is only several picoseconds long even for extended sources [9]. Additionally, higher laser intensity yields brighter  $K_{\alpha}$  sources while thermal x-ray yields decrease [4, 7, 8]. The former is due to increased inner-shell ionization for the higher energy electrons produced by high intensity short-pulse lasers, while laser-plasma interaction instabilities reduce target coupling of high intensity nanosecond laser pulses.

In this letter we show that a gas jet target is an efficient inner-shell emitter when irradiated by an ultra-short pulse laser, yielding high conversion efficiency into  $K_{\alpha}$ -like inner-shell x-rays. We measured total inner-shell conversion efficiency, integrated from  $K_{\alpha}$  to  $K_{\beta}$ , exclusive of the He-like lines, to be an order of magnitude more than in saran targets. Conversion efficiencies into near-cold (ionization state  $Z \leq 10$ )  $K_{\alpha}$  are between  $5 \times 10^{-6}$  and  $1 \times 10^{-5}$ , the same as found in previous ultra short pulse laser experiments with saran foil targets [4]. Near-cold  $K_{\alpha}$  is interesting for applications that require a spectrally narrow source, such as scattering, and the brighter total inner shell emission is important for backlighting applications. Unlike typical extended sources [6, 7], a gas jet is inexpensive, can operate at a high rep-rate, and produces no debris. The maximum yield into inner shell  $K_{\alpha}$ -like emission

is  $2 \times 10^{11}$  photons per joule of laser energy into  $4\pi$ .

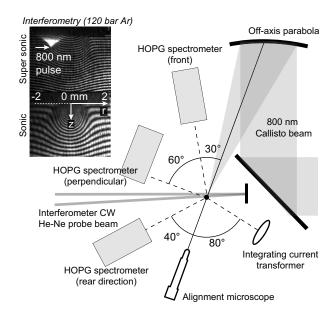


FIG. 1: Experimental setup (top view). The edge of the gas jet is placed at the focus of the 800 nm beam as shown in the inset. X-ray spectra are captured by the HOPG spectrometers, and hot electrons that escape the target are counted by the integrating current transformer.

We used 800 nm pulses from the Callisto ultra short pulse laser at the Lawrence Livermore National Laboratory. Callisto provides up to 10 J with approximately 150 fs pulse length, for a peak power of 100 TW. The beam was focused with an f/2 or f/3 off-axis parabola to a  $1/e^2$  focal spot diameter of 4  $\mu$ m, giving a vacuum intensity of  $10^{20}$  W/cm<sup>2</sup>. The typical pre-pulse contrast ratio on the Callisto laser has been estimated to be  $10^{-6}$ .

The gas jet target fired downward (the top view is shown in Fig. 1) and was aligned to an accuracy of 50  $\mu$ m. Our gas jet nozzle was mounted directly on a high-pressure solenoid valve driven by 150 V DC, pulsed for 30 ms.

X-ray spectrometers consisting of graphite (HOPG) crystals in the mosaic focusing mode [1, 10] dispersed incoming x-rays onto absolutely calibrated charged-coupled devices (Andor cooled CCDs) or absolutely calibrated image plates (Fujifilm BAS-TR). Conversion efficiency was calculated by integrating the detected counts [4, 10]. The spectrometers observed the front, perpendicular, and rear directions of the target, as seen in Fig. 1. High levels of noise in the spectra from the rear spectrometer, due to the flux of hot electrons out of the rear side of the target close to the laser cone, motivated preferential use of the front and

perpendicular views for our analysis.

A Lloyd's mirror interferometer [11] was used to diagnose the neutral density of the gas jet, as well as to see the hot spot formed by the pulsed laser, a fiducial that verified target alignment (cf. Fig. 1). The interferometer consisted of a continuous-wave He-Ne laser beam that was expanded to 30 mm diameter. The uppermost part of the interferometry beam probed the gas jet, while the lowermost part served as the reference beam. There was no significant perturbation of the reference part of the beam as the gas jet diffused away within 6-12 millimeters, less than the size of the expanded beam.

We used an integrating current transformer (ICT) from Bergoz to directly measure the flux of charged particles off the target (i.e. hot electrons) at 20° from the rear side of target. The ICT sensitive area is approximately  $10^{-3}$  sr and it can integrate picosecond pulses with a sensitivity of 2.5 V· s/C. The coil was mounted in a shielded configuration with 1 cm of Al, open in the center, to allow hot electron flux through the coil while preventing hot electrons from striking the coil itself.

X-ray spectra from 3.5% Cl gas (balance N), saran foil, and 100% Ar gas are shown in Fig. 2. The Cl spectrum is predominantly near-cold  $K_{\alpha}$  with some higher ionization features. In the case of Ar, the spectrum is more "comb" shaped, with many  $K_{\alpha}$ -like higher ionization features up to thermal He-like emission [12]. Both x-ray spectra are high contrast with low background noise, a very important attribute for short-pulse laser x-ray sources [13].

Shots onto the 3.5% Cl gas jet target and several reference shots onto saran foils ( $C_2H_2Cl_2$ , i.e. 33% Cl) allowed us to directly compare our gas jet conversion efficiencies with a large body of previous work on solid targets. We found that the near-cold Cl  $K_{\alpha}$  conversion efficiency was the same for both targets, correcting for concentration of Cl, even though the lower density and larger gas jet target has an optical depth roughly 1/10 the optical depth of the solid target ( $n_{\text{gas}}/n_{\text{foil}} \approx 10^{-3}$ ,  $\ell_{\text{gas}}/\ell_{\text{foil}} \approx 10^2$ ). Additionally, the total conversion efficiency into inner-shell x-rays (integrated from  $K_{\alpha}$  to  $K_{\beta}$ , exclusive of the He-like lines) is an order of magnitude higher in a 100% Ar gas jet than the Cl solid, i.e.  $10^{-4}$  for Ar gas compared with  $10^{-5}$  for saran. This is a direct comparison of solid and gas targets shot under the same experimental conditions and laser parameters. The additional emission is from inner-shell transitions in ionized Ar up to the Li-like state.

The HOPG curved crystal measurements indicate that the source size of the inner-shell  $K_{\alpha}$  lines is less than 1 mm in the horizontal and vertical directions. Future measurements

will investigate the source size with greater precision using two-dimensional monochromatic imaging with quartz crystals.

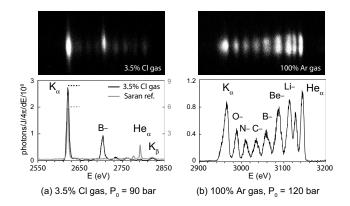


FIG. 2: Front side time-integrated HOPG x-ray spectra from (a) 3.5% Cl gas and saran reference; (b) 100% Ar gas. Both gas spectra were taken from a conical super sonic nozzle.

Clusters are solid-density particles that nucleate and form in higher-Z gas jets, such as Ar or Kr, due to adiabatic expansion upon exiting the nozzle [14]. In previous work, thermal  $Ly_{\alpha}$  and  $Ly_{\beta}$  emission from He gas jets irradiated by short-pulse lasers was enhanced [15, 16] by mixing in a higher-Z strongly clustering dopant gas. However, no inner shell emission from the higher-Z dopant gas was observed, presumably due to lower laser intensities.

In this study, to investigate the effects of both clustering and a different density profile on Ar  $K_{\alpha}$ -like inner-shell emission, we used super sonic and sonic nozzles. Our super sonic nozzle was conical with  $d_{\text{exit}} = 2$  mm, throat diameter  $d_{\text{crit}} = 1$  mm and an expansion length of 6 mm. The exit flow Mach number was measured via the flow expansion angle to be 3.2, close to the predicted value of 3.5 [17]. Our sonic nozzle was a 1 mm straight hole. An Abel inversion analysis of the interferometry fringe shifts indicates a neutral target density for backing pressures  $P_0$  near 120 bar of 1 ×10<sup>20</sup> cm<sup>-3</sup> on-axis near to the nozzle exit for the super sonic nozzle and 6 ×10<sup>20</sup> cm<sup>-3</sup> for the sonic nozzle, respectively, comparable to previous results [17].

The free expansion and correspondingly higher temperature in the sonic gas jet indicates that clustering (and therefore cluster-based emission) is lower relative to a super sonic gas jet; the effect on clustering due to nozzle choice has been confirmed elsewhere via Rayleigh scattering [18]. We see the effect of lower clustering via our conversion efficiency measurements. Conversion efficiency is  $10^{-5}$  (near-cold  $K_{\alpha}$ ) and  $10^{-4}$  (total) in the gas jet from the

super sonic nozzle; in the sonic nozzle, both conversion efficiencies are an order of magnitude lower (not shown).

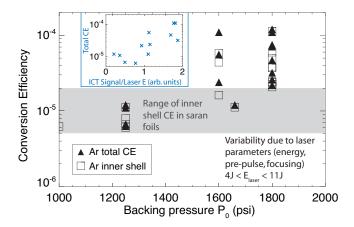


FIG. 3: (Color online) Front and perpendicular conversion efficiencies vs. backing pressure (main plot) and integrating current transformer signals (inset).

Conversion efficiency depends on the backing pressure  $P_0$  (i.e. the neutral density), as seen in our measured conversion efficiencies in Fig. 3. Static gas fills achieve the best conversion efficiency at high pressures near the critical density [7]; higher pressure also enhances clustering [14] in gas jets. The highest conversion efficiencies also require that the laser be focused close to the nozzle ( $z \approx 0.5$  mm) and near the front edge of the radial density profile (-1.8 mm  $\geq r \geq$  -1.2 mm), as expected due to ionization-induced defocusing [19].

The integrating current transformer measured total hot electron flux from the target. As can be seen in Fig. 3, high hot electron flux correlated with high conversion to x-rays.

Measurements of conversion efficiency are estimated to have relative errors of less than 10% due to uncertainty in the HOPG crystal reflectivity, spectrometer alignment, and noise in the spectra. There is a reproducibility factor of 60% due to the high sensitivity of innershell emission to laser pre-pulse and the variability in this laser parameter. The ICT signals are estimated to have a relative error of less than 5% due to the hardware integration circuitry.

In conclusion, the total inner-shell x-ray conversion efficiency integrated from  $K_{\alpha}$  to  $K_{\beta}$  is an order of magnitude higher in a gas jet than in a solid target, important for applications that demand high x-ray luminosity from a debris-free source. Future studies will investigate

higher energy x-rays (via higher Z gases) and utilize temporally resolved diagnostics to characterize the temporal resolution achievable with gas jet x-ray backlighting.

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